DEVELOPMENT AND OPERATION OF A SOLID-STATE SWITCH FOR THYRATRON REPLACEMENT*

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Abstract

A solid-state switch, consisting of 22 reverse conducting thyristors, has been designed to operate at 20 kV hold-off voltage, 1500 A peak, 57 ARMS, 1.0 µs pulse-width, and 4500 pps. To date, 70 switches have been fielded, accumulating over 330,000 unit-hours with a demonstrated MTBF of over 6000 hours. The previously used thyratrons have all been replaced since the solid-state switch has proven to be more reliable. In addition, the solid-state switch is more cost effective due to its ability to be repaired.

This paper discusses the design, construction, triggering, operation, reliability, and failure modes of this switch.

Introduction

The reason for developing a solid-state switch to replace thyratrons was driven by the reliability requirements of the Copper Laser System as part of the Laser Isotope Separation Program at Lawrence Livermore National Laboratory. The switches are installed in equipment that operates continuously, 24 hours/day, 7 days/week. There is an ongoing Reliability, Availability, and Maintainability (RAM) Program for this laser system. Part of the RAM process is to collect operation hours and failure data. To date, over 330,000 unit hours have been accumulated on 70 solid-state switches. It will be shown that the solid-state switch is six times more economical to operate than the best thyratron tried. This is due to its five times better reliability and to its ability to be repaired.

Application

In the copper laser application, the requirements for the switch are:

Hold-off voltage	20 kV
Peak current	1250 A
RMS current	57 A
Pulse-width	1.0 µs
Average power processed	35 kW
Repetition frequency	4,500 pps
Rate-of-rise	3000 A/ms
Jitter	±1.0 ns

The function of the switch is to discharge an intermediate energy storage capacitor into the magnetic compression circuit that powers a copper laser. The switch and compression circuitry are housed in the pulsed power electronics assembly for the copper laser amplifier package. This application is described in detail in reference one.[1]

Solid-State Switch Description

The solid-state switch is a system encompassing a stack of 22 circuit card assemblies, a magnetic assist, and a trigger chassis. Each circuit card assembly contains a reverse conducting thyristor (RCT), a resistor capacitor network, and triggering circuitry. A schematic of the circuit card assembly is given in Fig. 1; a photograph of the stack assemblies is given in Fig. 2.

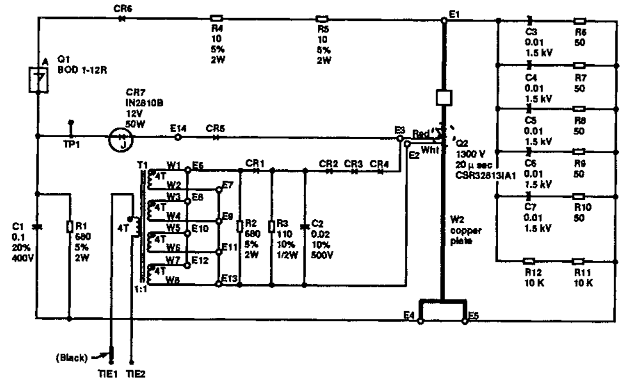

Figure 1. Schematic of circuit card assembly.

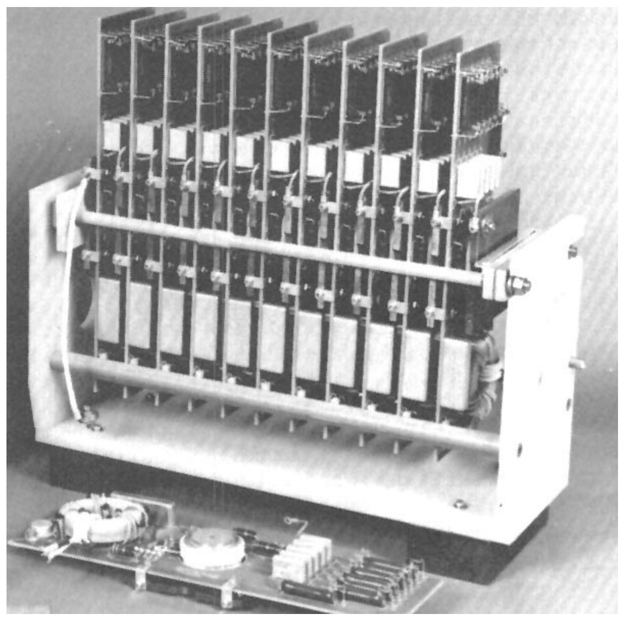

Figure 2. Photo of assembled solid-state switch and card, right side only.

The RCT has ratings of 1300 V hold-off, 20 µs recovery time, 325 A average current, and also a highly interdigitated gate structure. An asymmetric device was chosen for its lower on-state losses and faster recovery time. In addition, the voltage rating of this device in combination with its interdigitated gate structure provides for a higher plasma spreading velocity, resulting in larger di/dt capabilities.[2,3,4] The RCT incorporates a monolithic, anti-parallel diode simplifying the construction of the switch assembly by providing a protection diode for the asymmetric thyristor.

The magnetic assist is crucial to the successful operation of the switch. The purpose of the magnetic assist is to delay the main current pulse until the RCT is sufficiently turned on to accommodate the large peak current.[5]

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14. ABSTRACT
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The trigger wave shape, rise time, peak value, and pulse-width is critical for reliable, fault free operation of the RCTs. Triggering of the switch assembly was achieved using a single pulser to simultaneously drive the individual pulse transformers for each RCT. Primaries of 11 pulse transformers were connected in series; the two sets of primaries were then connected in parallel. Once the trigger wave shape was determined, this trigger scheme was very successful.

The resistor-capacitor network serves two purposes: First, a classical voltage snubber and, second, an energy store to aid the turn-on process of the RCT.[6]

The synergistic interaction of the hold-off time of the magnetic assist, energy stored in the resistor-capacitor network, and the trigger wave shape, provides for successful operation. The strong interplay among these parameters requires custom tuning for each different application.

Switch Development

The most challenging aspect of this switch's development was obtaining successful operation at the one microsecond pulse-width and 1250 A peak current. Due to the 1 μs pulse-width, the RCTs never fully turn on. Instead, only the area along the interdigitation conducts current. In addition, the time it takes for this area to conduct is dependent upon the triggering, the energy stored in the resistor-capacitor network, and the rate of deposition of this energy into the RCT. It should also be noted that the RCT chosen has an amplifying gate structure. To understand how these parameters interact, a small number of parametric tests were conducted on a single device. These included gate current requirements, energy stored in the resistor-capacitor network, the time constant of the resistor-capacitor network, and the time delay of the magnetic assist. Also performed was a series of thermal tests to determine the minimum size cold plate to be used with the Freon immersion cooling.

Figure 3 gives a typical current pulse in the switch. Note, there are two positive half-sinusoids; the first is the normal discharge of the intermediate store capacitor, and the second results from a reflection off the load traveling back to the switch. This second pulse drove the pulse-width of the trigger pulse; it was decided to have a sufficiently long trigger pulse to inject the gates during this second pulse. Figure 4 gives a typical trigger pulse at the output of trigger chassis. A parameter study of the gate current was performed. It was found that the RCTs would survive with a gate current as small as 0.5 A and as large as 20 A for the wave shape given in Fig. 4. The value for the peak of the gate current was chosen to be about 7.5 A per device.

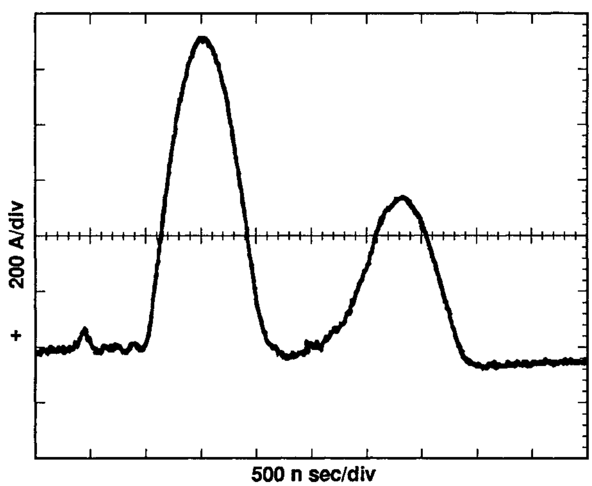

Figure 3. Typical switch current waveform.

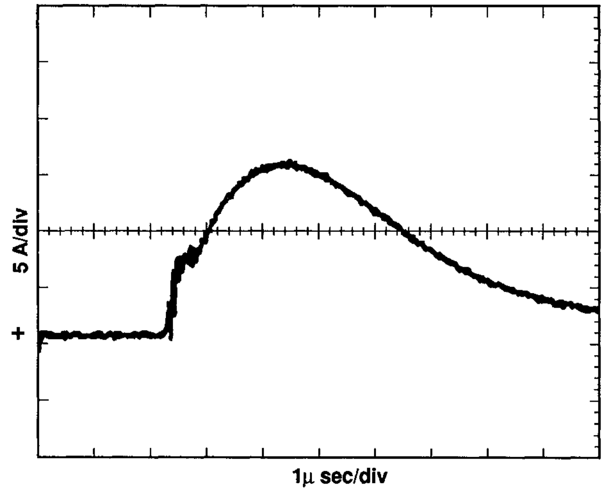

Figure 4. Total gate current from trigger chassis.

It has been stated in the literature that very large gate drives allow for the conduction of very short pulse widths.[5] This effect was not very pronounced for this application. This results from the fact that the RCT uses an amplifying gate and that the di/dt is small in comparison to that quoted. Also, perhaps that because of the interaction of both the magnetic assist and the resistor-capacitor energy store, this effect was not noticed. In this application, the gate current was chosen so as to reduce the requirements on the trigger chassis. This allowed an existing thyratron trigger chassis, with slight modification, to be used to trigger the solid-state switch.

The gates are voltage source triggered. In the early development of the switch, a current driven gate system was employed. This was abandoned since the jitter requirement of ±1 ns could not be met. This appeared to be more of an electronics problem than a inherent problem in the stack. The voltage source triggering scheme demonstrates a switch jitter of less than 1 ns.

The hold-off time of the magnetic assist was varied; data was collected at 200, 400, 600, and 800 ns. The resistor-capacitor network was varied as well; data was collected for resistance values of 1.25, 2.5, 5.0, and 10.0 ohms and capacitance values of 0.05, 0.1, 0.2, and 0.25 μF. During these parametric studies, the voltage across the single device and the current through the device were monitored. Performance was judged by estimating the conduction loss in the device. This usually correlated to the lowest voltage across the RCT. There was not one global optimum; the values chosen for construction of the switch system was based on a desire to minimize the system loss; therefore, the smallest value of capacitance was chosen, along with a magnetic assist hold-off time of 500 ns. The resistance value of 10 ohms gave the lowest conduction loss for the other values chosen. J. Vitins discusses the interplay of these variables more extensively in his papers.

In developing the switch system, it was found that more was not always better. After our parametric testing of a single device, a 20 high stack was constructed using values of 0.25 μF and 2 ohms for the resistor-capacitor network. While this gave very low conduction losses, a large number of devices would fail for reasons that were not understood. It was subsequently discovered that the devices were failing because excessive power was being dissipated in the amplifying gate due to the large energy store. Successful operation for a few hundred hours was only achieved after reducing the capacitance value to 0.1 μF. This caused another evaluation of the parameters resulting in the present choice of minimum capacitance.

Also, included in the switch development was a method to protect the stacks from overvoltages that would result in the destruction of all the RCTs. The protection scheme employed uses break-over diodes (BODs) to initiate triggering of the RCTs whenever the voltage across the circuit card assembly exceeds the rated voltage of the BOD. This method has proven very reliable. The stacks self trigger during an overvoltage. This action mimics a thyratron that can no longer hold off voltage. This protection method allows the performance of the stack to degrade gracefully. Usually some number of RCTs can be shorted before the overall operation of the switch becomes a problem resulting in a repair action. Typically, in our application, three to four RCTs need to be replaced when the switch can no longer hold-off the required operating voltage.

Circuit Operation

During the initial testing of the solid-state switch in the pulsed power electronics assembly, a significant operational difference from the thyratron was noted. This difference is the energy lost in the solid-state switch. The energy loss has two components: First, the conduction loss of the solid-state switch is higher than the thyratron and second, the energy stored in the resistor-capacitor network across each RCT must be supplied.

The energy required for the resistor-capacitor network can be calculated from 1/2*C*V**2*f, the energy stored per pulse times the pulse repetition frequency. Since the circuit is resonantly charged, there is very little energy dissipated in the charge cycle; it is assumed that all the energy is lost in the discharge of the network. This loss results in an increased demand on the power supply that charges the magnetic compression circuit. In this application this loss is about 2.4%.

The second loss was characterized by energy measurements performed on the energy transferred from the first capacitor to the second capacitor in the magnetic compression circuit. The voltages on the first capacitor and the second capacitor were measured using Tektronic P6015 high voltage probes and a Tektronic 2430 oscilloscope. In order to compensate for this loss, the value of the first intermediate storage capacitor was increased from 45 to 48.6 nF. The value of the second capacitor remained at 45 nF. The decrease in voltage is attributed to the loss in the switch since this loss is much greater than the resistive circuit losses. The data is given in Table 1. Since the data given in Table 1 was taken on two different pulsed power assemblies and also a few months apart, the absolute voltages cannot be directly compared, however, the relative loss is accurate.

Table 1. Energy transfer comparison.

Thyratron:

Power Supply Voltage (kV)	C_0 = 45 nF Voltage (kV)	C_1 = 45 nF Voltage (kV)	Energy Last %
6	11.25	11.12	2.4
7	13.15	13.0	2.4
8	15.0	14.	4.0
9	16.9	16.5	4.7
10	18.5	18.2	3.4
11	19.8	19.	3.4

Solid-State Switch:

Power Supply Voltage (kV)	C_0 = 48.6 nF Voltage (kV)	C_1= 45 nF Voltage (kV)	Energy Last %
6	10.0	9.90	11.1
7	11.7	11.5	10.5
8	13.5	13.3	11.2
9	15.0	14.7	11.1
10	17.0	16.7	10.7
11	18.5	18.13	9.4

From Table 1, there are two conclusions: First, the solid-state switch has a greater loss than the thyratron, and second, the relative loss is greater at lower voltages. The increased relative loss can be explained because RCTs have relatively constant on state voltage drops as compared to thyratrons. This results in the solid-state switch having a voltage drop across it that is not very dependent on the current conducted by it giving the larger relative loss. In this application the increased relative loss is about 7%; the solid-state switch loss is about 10% and the thyratron loss is about 3%.

Not all the energy lost is dissipated in the RCTs or thyratron. The loss given in Table 1 is the combination of magnetic assist losses, thyratron or stack loss, and resistive circuit loss. The magnetic assist for the stack is comprised of 12 cores; the magnetic assist for the thyratron is comprised of 2 cores of the same material and size as those used for the stack. The magnetic assist for the stack is larger to provide for the increased hold-off time required. The core loss for the magnetic assist is a significant fraction of the energy lost; however, it is appropriate to call this part of the "switch" since the stack will not operate correctly without the magnetic assist. References 3 and 4 discuss RCT losses in greater detail.

In this application, the additional power required to accommodate these losses is about 10%.

Operational Experience

To date, about 70, 22-high stack assemblies have been built and operated in the Copper Laser System, accumulating over 330,000 unit hours. The first switches were deployed on a trial basis in 1988. In October of 1989, a decision was made to use solid-state switches in all of the laser amplifiers. Most of the 70 assemblies were deployed after January 1990. Figure 5 is a plot of the Mean Time Between Failure (MTBF) for the stacks from March 1990 to February 1991. This graph is based on an accumulation of all failures and operating hours. A failure is defined as a malfunction of the laser assembly caused by the switch regardless of the number of RCTs or other switch components replaced. The graph shows the growth in reliability for the switches. It is expected that the curve will flatten out in the 7000 to 8000 hour range. This expectation is based on Fig. 6: Fig. 6 is a plot of the three-month moving average of the MTBF. This is calculated using only the failures and operating hours during a given three-month period. The three-month moving average MTBF is used as the best measure of current operation.

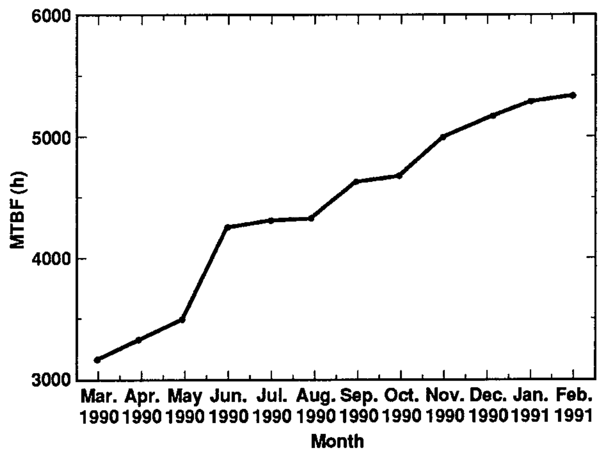

Figure 5. Cumulative MTBF of solid-state switch.

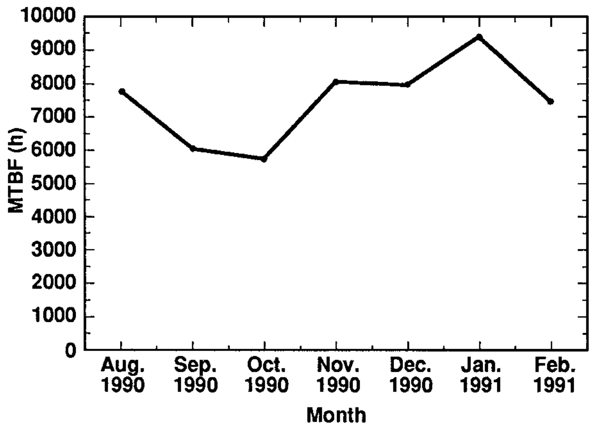

Figure 6. Three-month moving average MTBF of solid-state switch.

In order to compare the solid-state switch to thyratrons, the life of the thyratron must be described. For this particular application, a Weibull plot of thyratron life has been generated (see Fig. 7), based on the failure of over 200 tubes from the best performing vendor. From this curve, there are two important points: The first is that all tubes fail before 2500 hours. The second is that characteristic life is about 1200 hours. The characteristic life is defined as the time when the percent failed reaches 63%. Two other vendors performed significantly poorer, having characteristic lives of 600 hours and 800 hours.

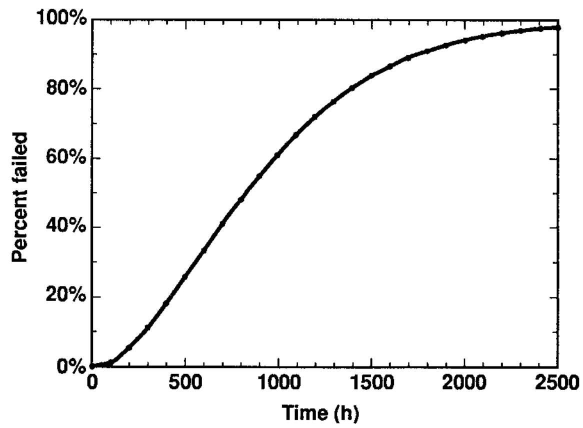

Figure 7. Weibull plot of thyratron life.

It is important to note that since the solid-state switches can be repaired, it is appropriate to use MTBF as the measure of reliability. When thyratrons fail, they are removed and discarded; the appropriate measure of reliability is the characteristic life. From Fig. 6, the stack reliability, measured in terms of MTBF is currently about 7000 hours; Fig. 7 shows that the best thyratrons lasted 2500 hours. The characteristic life for thyratrons was about 1200 hours: This should be compared to the MTBF for the solid-state switch. The experience to date demonstrates that solid-state switches in the copper laser application are about a factor of five more reliable.

Figure 5 indicates a factor of two increase in reliability over about a one-year period. There are two aspects to this growth. First, there is almost always a growth in reliability for a new product due to improved procedure, elimination of design errors, elimination of manufacturing flaws, etc. Second, in this particular application, there was also a discernible infant mortality problem with the RCTs themselves. Figure 8 shows the failure rate of the RCTs versus time. This plot mimics the classic "bathtub" curve. There was a relatively high failure rate for the RCTs during the first thousand hours; subsequently, the failure rate follows the "normal" trend for electronics, that is, slowly decreasing with time.

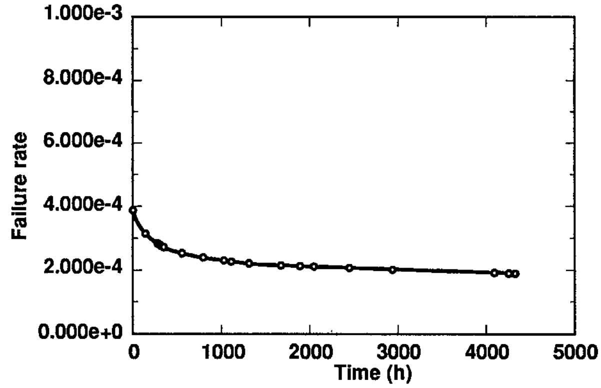

Figure 8. Failure rate of solid-state switch.

The reliability of the switches is enhanced by the fact that the switches degrade gracefully, as mentioned above, allowing the switches to be repaired under a preventative maintenance program. Typically, more than one RCT needs to be replaced when a switch fails, i.e., it causes the PPE assembly to become nonfunctional. A preventative maintenance program has been instituted that replaces failed RCTs whenever the pulsed power electronics assemblies are repaired for other reasons. These repair actions are not counted as switch failures since the switch did not cause the laser assembly to fail.

The "life" of a solid-state switch for this application has not been determined. Theoretically, as long as the switches are repairable, the assembly can be continued to be used. In this application, since the assemblies are immersed in Freon, there appears to be an upper limit of perhaps 20,000 hours. This is mostly a result of degradation to the circuit card assemblies, particularly loss of solder connections. A parylene coating is being tried to extend the life of the assemblies. The experience to date has been that a few, three to four, switches have exceeded 13,000 hours total life. About ten switches have exceeded 5000 hours without failure. Likewise, switches that have been repaired have exceeded 7000 hours before an additional failure.

The increased reliability of the switch caused the MTBF of the pulsed power electronics assembly to increase from about 1000 hours to over 3000 hours.

Failure Modes

During the parametric studies and the initial deployment of the switches, all failed RCTs were cut open to determine the location of the failure. In all RCTs investigated, the failure occurred at the outer peripheral of the amplifying gate or along the fingers of the interdigitation structure. The failures appear as burn spots: Depending on the length of time between failure and removal, the "spot" can become a hole.

The RCTs are very susceptible to failure due to a "weak" gate drive. In order to prevent failures, protection circuitry was added to the trigger chassis. This circuitry monitors the power supply voltage of the trigger circuit and the voltage across the switch. The voltage across the switch is monitored to ensure that the energy store in the resistor-capacitor network is sufficient. The power supply voltage is monitored to ensure the trigger level is sufficient. Adding this protection circuitry has significantly contributed to the reliability growth.

Cost Considerations

The initial cost of a solid-state switch is about a factor of two more than that of the thyratron they replaced. In lots of 100, the thyratrons cost between $6,000 and $7,000 each. The switch assemblies cost about $13,000 each; more than half is the cost of the RCTs. The trigger chassis for a thyratron and stack assembly are comparable. There is no requirement for a filament/reservoir power supply for the solid-state switch.

The cost to use thyratrons as switches is the initial cost divided by their characteristic life: $6,700/1,200 or $5.58/hour. The cost of a solid-state switch needs to account for the repair costs. Given a 20,000 hour life, a 7,000 hour MTBF and a repair cost of $1,500, the solid-state switch cost becomes (13000+3*1500)/20,000 or $0.88/hour. This is about a factor of six less than the thyratron cost.

Conclusion

Seventy (70) solid-state switches have been deployed, accumulating over 330,000 operating hours. The reliability of these switches has been shown to be a factor of five better than the thyratrons they replaced. The solid-state switches are also a factor of six less expensive than thyratrons, considering capital and operating costs. The electrical performance of the solid-state switches are nearly identical to the performance of the thyratrons as well.

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